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PreCam: A Step Towards the Photometric Calibration of the Dark Energy Survey

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Abstract. The Dark Energy Survey (DES) will be taking the next step in probing the properties of Dark Energy and in understanding the physics of cosmic acceleration. A step towards the photometric calibration of DES is to have a quick, bright survey in the DES footprint (PreCam), using a pre-production set of the Dark Energy Camera (DECam) CCDs and a set of 100 mm×100 mm DES filters. The objective of the PreCam Survey is to create a network of calibrated DES *grizY* standard stars that will be used for DES nightly calibrations and to improve the DES global relative calibrations. Here, we describe the first year of PreCam observation, results, and photometric calibrations.

1. PreCam Survey

The PreCam Survey is a quick, bright survey within the footprint of the Dark Energy Survey (DES Flaugher 2005; Flaugher et al. 2010) in the DES *grizY* filter system using a small mosaic camera of DECam CCDs, a 2×2 array of 2048×2048 CCDs with 15-micron pixels.[1] PreCam was built by the PreCam Argonne group (Kuehn et al. in prep.) and placed on the University of Michigan Department of Astronomy's Curtis-Schmidt (C-S) telescope at Cerro Tololo (CTIO). A major goal of the PreCam Survey is to provide an improved photometric calibration for the DES using an ≈1/32-nd scale version of the DECam, and calibrating many bright stars (hundreds per square degree fainter than the DES saturation limit) across the DES footprint in the DES 5 filter system. The PreCam Survey would thus provide several benefits to the DES photometric calibrations (Tucker 2005; Tucker et al. 2007, 2010), including:

1. extinction standards throughout the DES footprint, permitting better nightly photometric solutions during DES operations;

2. an additional layer of observations across the DES footprint, allowing for improved global relative calibrations, helping DES achieve its requirement of 2% global relative calibrations sooner and helping DES achieve its long-term goal of 1% global relative calibrations;

3. good transformations relations between the SDSS and DES photometric systems via PreCam observations along the SDSS equatorial Stripe 82; and

[1]For characterization for these devices, see Estrada et al. (2006, 2010).

4. Y-band standard stars (for which there is currently a great lack).

For more details about the DES photometric calibrations, see Tucker (2012)[2].

2. PreCam Survey Strategy

The PreCam Survey aims to generate a catalog of reference stars within the DES footprint with magnitudes within the dynamic range of DECam and internally calibrated with relative precision of 1%. The PreCam survey strategy is to image approximately 500 square degrees (10%) of the DES footprint with multiple (approximately 10) tilings in the $grizY$ filters, in a sparse grid pattern shown in Figure 1. PreCam imaging would extend down to 1.5 mag fainter than the point-source saturation limit of a nominal 100-sec DES wide-field survey science exposure. Stars from the resulting PreCam standard star network would be observed multiple times per night during the course of DES observing, helping to provide good anchor points for the global calibration of the DES.

On the C-S, the PreCam field-of-view is $1.6° \times 16°$(or 2.56 sq. deg), which allows the survey to be completed in a reasonable amount of time. For our exposure time estimates, we assumed a 0.24 m^2 effective collecting area for the C-S (i.e., a 0.6m effective aperture and 15% obscuration); a 1.45 $''$ pixel size; and a moon-less sky with (AB magnitude) sky backgrounds of 21.7, 20.7, 20.1, 18.7, 18.0 mag/arcsec^2, for the g, r, i, z, and Y filters, respectively. Table 1 summarizes our exposure time findings. For example, we estimated to reach the requisite depth of 17.8 for r-band – i.e., 1.5 mag fainter than the nominal DES science exposure saturation limit of $r \sim 16.3$ – we needed an r-band exposure time of 51 sec. Furthermore, this exposure time would also let us measure stars from a PreCam saturation limit of $r \sim 13.2$ to a nominal faint limit of $r \sim 20.7$ ($S/N = 5$). For creating a good set of standard stars, we are mostly concerned with those stars with $S/N > 50$, and we estimate that, for a typical r-band PreCam exposure with this exposure time, would have about 265 such stars per square degree. In the final column, we list the actual $S/N = 50$ depth for a single exposure with the given exposure time in each filter, based on observations from PreCam's first season, which is noticeably brighter than originally estimated (e.g., about 1.2 mag brighter than the estimate for r-band). We attribute much of this difference to the fact that, due to manufacturing issues with the new secondary mirror that the PreCam was providing for the C-S, we had to re-install and use the original secondary mirror, which experiences substantial vignetting. Fortunately, multiple observations of each part of the PreCam sky allows us to achieve our original goals via catalog-level coaddition.

Using these estimated exposure times, a 10-sec read out time for the CCDs, the required number of repeated observations for the planned grid footprint, and reasonable overheads, we estimated that we would need about 100 nights on the C-S would to reach our goals. For that reason, two observing runs with a total of 100 nights were requested from the University of Michigan Department of Astronomy for observing time on the C-S Telescope in late-2010 and early-2011.

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[2]https://indico.fnal.gov/getFile.py/access?contribId=8&sessionId=8&resId=0&materialId=slides&confId=4958

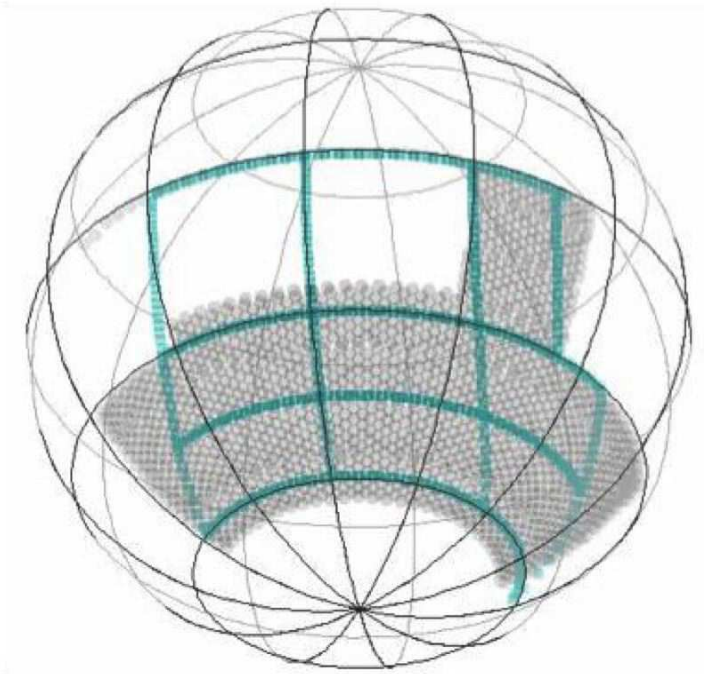

Figure 1. The PreCam Survey plan as of August 2010. Shown in gray is the proposed DES survey footprint, with the ~ 500 sq deg (10% DES area) PreCam gridwork overplotted in cyan. The size of the cyan symbols are drawn approximatly to the scale of the PreCam FOV (1.6°x1.6°). The plan is to cover the grid 10 times in each filter (*g*, *r*, *i*, *z*, *Y*). Note that the planned DES footprint was modified from what is shown here at the end of May 2012.

Table 1. Exposure Calculations for Point Sources in the Baseline PreCam Survey.

Band[a]	Exp. Time[b] [sec]	PreCam Sat. [c]	DES Sat. [d]	PreCam S/N=50[e]	PreCam S/N=5[f]	# Stars per sq deg[g]	Measured S/N=50[h]
g	36	12.8	16.3	17.8	20.9	186	16.8
r	51	13.2	16.3	17.8	20.7	265	16.6
i	65	13.4	16.2	17.7	20.5	344	16.3
z	162	14.1	16.0	17.5	20.1	317	16.2
Y	73	11.6	14.3	15.8	18.5	150	14.7

[a]The filter band.

[b]The chosen PreCam exposure time.

[c]The estimated saturation limit of PreCam at the chosen exposure time.

[d]The estimated saturation limit of a nominal 100-sec DES wide-field survey science exposure.

[e]The estimated magnitude at which a PreCam point source would, for the chosen exposure time, have a S/N of 50.

[f]The estimated magnitude at which a PreCam point source would, for the chosen exposure time, have a S/N of 5.

[g]The estimated number of stars per square degree with $S/N > 50$ in a PreCam exposure for the chose exposure time.

[h]The measured $S/N = 50$ faint limit for PreCam at the chosen exposure time, based on the first season of Precam observations.

3. Survey Operations

The PreCam Survey relies on its dedicated software for its nightly operation and communication with the C-S telescope control system. This software includes an earlier version of the software that will operate the DES survey data acquisition and control system and which is called the Survey Image System Process Integration (Di Marcantonio et al. 2008; Honscheid et al. 2010; Buckley-Geer et al. 2011, SISPI). PreCam SISPI coordinates all aspects of the camera operation and the observation sequences.

As a part of SISPI, the tactical observation package (ObsTac; developed by E. Neilsen of Fermilab) determines a sequence of pointings for the telescope based on a number of inputs, including the survey history (i.e., fields previously observed), survey strategy (e.g., the survey footprint and the nightly standard star fields to observe), as well as the current observing conditions (e.g., time of twilight and the location of the Moon).

SISPI supports simple scripting of a given series of exposures (pointing, flats, bias, focus, etc.) and provides standard features such as general purpose dither patterns and support for extra packages (e.g., the specialized focus script developed by S. Allam of Fermilab and the Quick Reduce pipeline developed developed by DES-Brazil).

A typical night of PreCam operations consists of the following. During the afternoon, a sequence of biases and darks are taken. A set of dome flats in each of the 5 *grizY* filters are taken at sunset (taking them at sunset helps avoid changing light patterns on the dome flat screen due to light leaks in the C-S dome). Soon after sunset, a bright star is observed to initialize the telescope's pointing. About 30 minutes after sunset, a quick focus sequence is taken of a globular cluster in r-band; we use a globular cluster since the PreCam's field-of-view is large ($1.6^\circ \times 1.6^\circ$) relative to the angular size of the core of a typical globular cluster, but the globular cluster still provides lots of stars over much of the focal plane, which helps to map out the PreCam's "surface of focus" (in the PreCam Season 1, no field-flattener was used, so the focus changes noticeably over the PreCam field-of-view). About an hour after sunset (around the end of 12° twilight), the night's ObsTac queue of standard stars and target fields is started and runs through the night. When the Moon is down, ObsTac schedules target observations in either the g or r filter; when the Moon is up, ObsTac schedules target observations in the i, z, or Y filter. ObsTac also schedules low-, intermediate-, and high-airmass standard star field observations in all 5 filters for about 10 minutes roughly once an hour throughout the night (each standard star exposure is 10 seconds long, independent of filter); if the night is anticipated to be cloudy, there is an option to skip the standard star fields. During the night, the observers monitor the instrument, the data being taken (e.g., via the DES-Brazil Quick Reduce pipeline), and the sky conditions. At the beginning of morning 12° twilight, on-sky observations are concluded, the dome is closed, and a second set of dome flats is taken. At the end of the night, final touches are made to a manual log that was compiled over the course of the night, the data are transferred to Observatorio Nacional (Brazil) and to Fermilab, and the ObsTac log is uploaded to the ObsTac database. During the day, various tests and calibrations are performed remotely from Fermilab, Argonne National Lab, University of Michigan, Observatorio Nacional, and other DES institutions. Finally, in the afternoon, a daily telecon takes place between the C-S observers and remote members of the PreCam team to discuss issues and to review of the targeting and scheduling plan for the upcoming night (with options for modifications as needed based on weather predictions, and recommendations based on the previous night's instrument performance).

4. Season 1 Survey Observations

PreCam Season 1 included two main runs during the CTIO 2010B semester (July 2010 – January 2011). The first run, which ran from August 10 throught the night of September 27, consisted of two main parts. August was devoted to installation of the PreCam camera itself and its auxiliary systems (e.g., the PreCam readout electronics, new flat field system, and a new secondary mirror), as well as off-sky engineering and commissioning tasks. September was then devoted to on-sky engineering and commissioning tests, during which time an important manufacturing error was discovered in the new C-S secondary mirror, requiring the re-installation and re-collimation of the original secondary mirror.

The second, longer run ran from November 8 through the night of January 20 (minus the nights of December 24 and 25, on which CTIO was closed). The first several nights were spent on re-mounting and re-commissioning PreCam. We started obtaining useful survey data on the night of November 16 and were in full survey operations mode by the end of the month. Of the 64 nights available between November 16 and January 20, we obtained useful on-sky survey data on 51 nights, losing just one night to weather and ten nights to various hardware issues and using up a further two nights on end-of-run engineering tests, yielding an on-sky rate of approximately 80%.

The size of the full data set from both runs was ~0.6TB (gzip-compressed). From the 51 nights of on-sky survey data from the second run, we accumulated 24,443 frames, including bias, flat, dark, focus, stellar linearity test, standard star field, and survey field frames – of these frames, 3500 were of standard star fields (700 in each of the 5 filters), and 7520 were of survey fields (1888 in g, 1868 in r, 3152 in i, 269 in z, and 343 in Y).

Finally, we note that, due to the unexpectedly long commissioning of PreCam, it was necessary to reduce the scope of the project and perhaps seek a second season of comparable length. We did this by ignoring the extreme western edge of the planned PreCam footprint and by focusing primarily on the g, r, and i filters. The part of the footprint observed in in PreCam Season 1 is shown in Figure 2. It is the data from PreCam Season 1 that are described in the following sections. At the time of this workshop (April 2012), it is yet unknown if there will be future PreCam seasons.

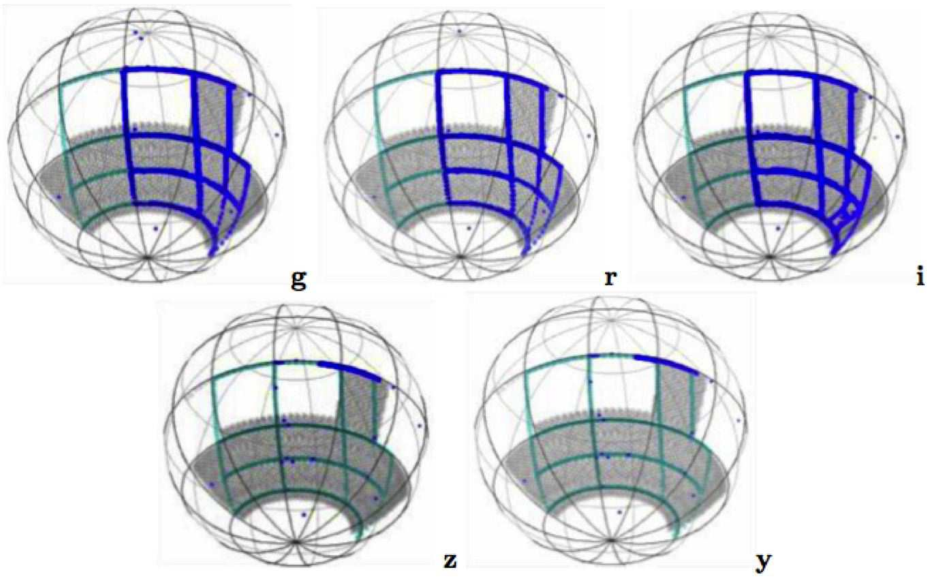

Figure 2. Actual PreCam Survey coverage as of January 20, 2011. Shown in blue are the positions of the observed science and standard star fields taken up through January 20, 2011, overplotted on the originally planned PreCam footprint (cyan) from Figure 1).

5. Data Reduction

The raw data are processed at Fermilab using a python-based pipeline developed by Tucker and Allam that will be documented more fully in Allam et al. (in prep). The reduction steps include removing spatially correlated readout noise ("horizontal banding and streaking")[3], correcting for the bias and flatfield, correcting bad pixels, and obtaining precise astrometry.

Extra care is taken during the data reduction step to automatically measure, flag, and remove the noise stamp due to the horizontal banding and streaking. A "streaking

[3]PreCam data suffered from high readout noise ("horizontal banding and streaking") throughout the full observing run, affecting almost all the raw data to various degrees.

flag" modules is used to monitor the quality of the resulting corrected images, tagging and culling those images that could not be sufficiently corrected for the correlated noise. In addition visual inspection is performed to ensure that only good images were included for further analysis.

After basic image detrending, a quick first-pass astrometric calibration pipeline is run on the reduced images, using the 2MASS PSC survey overlapping PreCam survey footprint, typically yielding an initial mean astrometric solution of $\sim 1.12''$RMS relative to 2MASS Skrutskie et al. (2006). When we refine our astrometric solution in a second-pass (which has an improved astrometric model), we use the UCAC4 catalog Zacharias et al. (2010), which typically yields a final mean astrometric solution of $0.3''$ RMS relative to UCAC4.

Next, we use SExtractor (version 2.8.6) to detect and extract sources in each filter. We note that its standard neural network for separating point sources from extended sources has been trained for values of seeing between 0.025 and 5.5 pixels FWHM and for images in the range of 1.5<FWHM<5 pixels, and is optimized for Moffat profiles with $2\leq \beta \leq 4$. These conditions are fulfilled for the PreCam observations on the C-S. Preliminary results from the PreCam version V3 data reductions are described in Kuehn et al. (in prep.). However, during the PreCam V3 data reductions, we discovered a systematic flat-fielding error that prompted us to create starflats based on PreCam observations within SDSS Stripe 82. These star flats are used in subsequent versions of the PreCam data reductions. Figure 3 shows the star flat correction for i-band as a function of position on the PreCam focal plane.

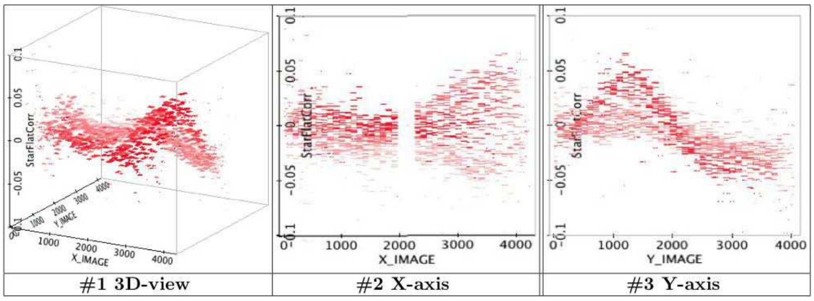

Figure 3. Three different views of the i-band PreCam star flat that was created by comparing PreCam observations in SDSS Stripe 82 against a Stripe 82 standard star catalog created by John Marriner.

Despite several hardware issues that dogged this first season of PreCam – including substantial vignetting on the edges of the focal plane, problems with the dome flat illumination system toward the end of the season, shutter failures, curvature in the surface-of-best-focus leading to variable PSFs across the focal plane, and the aforementioned horizontal banding and streaking), in the end the first-season PreCam footprint of usable data covered a non-unique area (primarily due to multiple tilings) of 17,679 sq. deg (3810.8, 3685.5, 6707.1, 1838.8, and 1637.1 sq. deg in g, r, i, z, and Y, respectively). Figure 4 shows the sky coverage for stars with 1% photometric errors or better in each of the 5 PreCam filter bands.

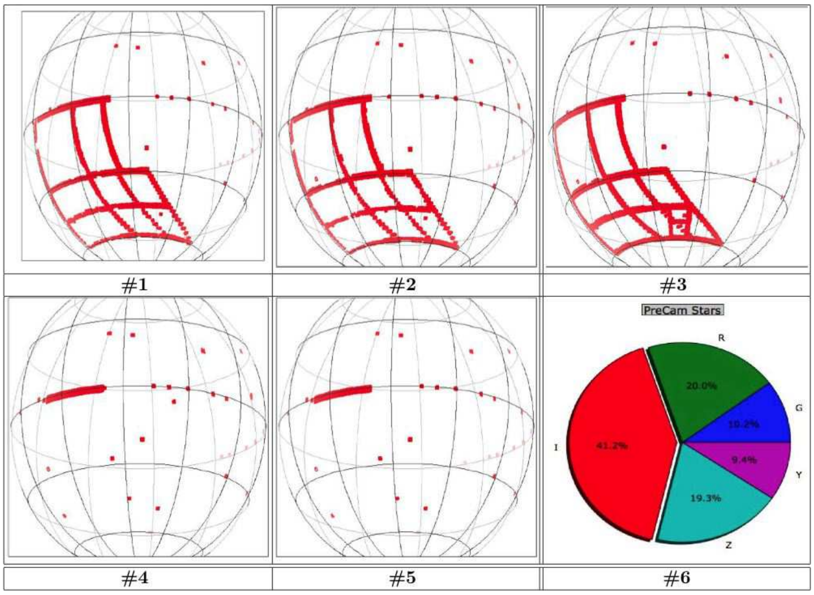

Figure 4. PreCam sky covered by stars with 1% or better photometric errors in the version V4 data reductions: #1: g-band, #2: r-band, #3: i-band, #4: z-band, #5: Y-band. In #6 we show the total fraction of these stars in each filter.

6. Photometric Calibration

The photometric calibration of the Precam data is an interative process, composed of both a nightly/intermediate calibration step and global calibration step. Both steps make heavy use of SDSS for a source of calibration stars – both in SDSS Stripe 82 and from 15 SDSS-related standard star fields (from the Smith et al. 2002 $u'g'r'i'z'$ standard star fields and the Southern $u'g'r'i'z'$ standard star fields[4] Smith et al., in prep.). For Y band, we make use of UKIDSS Lawrence et al. (2007) Y-band overlaps with SDSS Stripe 82. Below, we describe in turn each of the two main PreCam calibrations steps.

6.1. Nightly/Intermediate Calibrations:

For the nightly calibrations (a.k.a., intermediate calibration), we fit each night's standard star observations in a given filter band to a photometric equation of the following form, solving for a zeropoint (a), a first-order extinction (k), and an instrumental color term coefficient (b):

$$m_{inst} - m_{std} = a + b \times (stdColor_{inst} - stdColor_0) + kX,$$

where

- m_{inst} is the instrumental magnitude in that filter band as measured by SExtractor,
- m_{std} is the standard star magnitude in the SDSS system,

[4]http://www-star.fnal.gov/Southern_ugriz/New/index.html

- $stdColor_{inst}$ is the standard star color in the SDSS system,
- $stdColor_0$ is the "reference" or "fiducial" color for that filter, and
- X is the airmass of the observation.

Explicitly, for each of the 5 PreCam filter bands, this equation translates as follows:

$$
\begin{aligned}
&g_{inst} \text{ - } g_{SDSS} = a_g + b_g \times (g-r)_{SDSS} - 0.53) + k_g X,\\
&r_{inst} \text{ - } r_{SDSS} = a_r + b_r \times (g-r)_{SDSS} - 0.53) + k_r X,\\
&i_{inst} \text{ - } i_{SDSS} = a_i + b_i \times (i-z)_{SDSS} - 0.09) + k_i X,\\
&z_{inst} \text{ - } z_{SDSS} = a_z + b_z \times (i-z)_{SDSS} - 0.09) + k_z X,\\
&Y_{inst} \text{ - } Y_{UKIDSS} = a_Y + b_Y \times (z_{SDSS} - Y_{UKIDSS}) - 0.05) + k_Y X,
\end{aligned}
$$

We note that, at this step of the calibrations, we tie to the SDSS (+ UKIDSS Y) photometric system.

6.2. Global Calibration:

The first step in global calibration is converting all the calibration stars gathered so far – from SDSS Stripe 82, from the Smith et al. (2002) $u'g'r'i'z'$ standards and its Southern extension, from the UKIDSS Y-band data, and even from PreCam stars calibrated to the SDSS (+UKIDSS Y) as part of nightly/intermediate calibrations – to the PreCam *grizY* AB magitude system. Transformation equations to the PreCam system were calculated by running the `synphot` synthetic photometry package on the Pickles (1998) stellar library and the PreCam, SDSS, and UKIDSS filter responses and fitting the results for each PreCam filter band. Converting all the data to the PreCam *grizY* system permits us to proceed with rest of the calibrations without worrying about color cross-terms. In other words, once this is done, the next steps of the calibration of, e.g., the PreCam g-band star catalog are independent of the PreCam r-band catalog. This simplifies the remaining steps substantially.

Next, photometric zeropoints for each PreCam survey exposure are measured using the large amount of field-to-field overlap that was included as part of the PreCam survey strategy. This is done independently for each PreCam filter band. The "PreCam-transformed" calibration stars described in the previous paragraph are fed into the process in order to accomplish two tasks: (1) to tie the global relative calibrations to the AB magnitude system, and (2) to act as "anchor points" to prevent large-scale, low-amplitude systematic gradients in the relative calibrations. The code to do this, which is run iteratively, is called the Global Calibrations Module (GCM; Tucker et al., in preparation),[5] and it makes use of an algorithm described by Glazebrook et al. (1994).

Once the photometric zeropoints are calculated for each usable on-sky exposure in a given filter band, we apply the zeropoints to the stars in those exposures and make use of the multiple repeat observations of a given part of the sky to produce a catalog of averaged magnitudes in that filter. As an example, we show in Figure 5 the number of repeat observations per star in i-band. Note that, especially for the nightly standard star fields, the total number of repeat observations for a star can be over 100 (more typical, however, is about 4–5 observations per star in the main PreCam survey grid).

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[5] https://indico.fnal.gov/getFile.py/access?contribId=8&sessionId=8&resId=0&materialId=slides&confId=4958

Once the this process has been run for each of the 5 PreCam filters, the results are vetted, and a final catalog of well-calibrated stars is created. This new catalog of "PreCam standard stars" will be made publicly available for general user in a future paper.

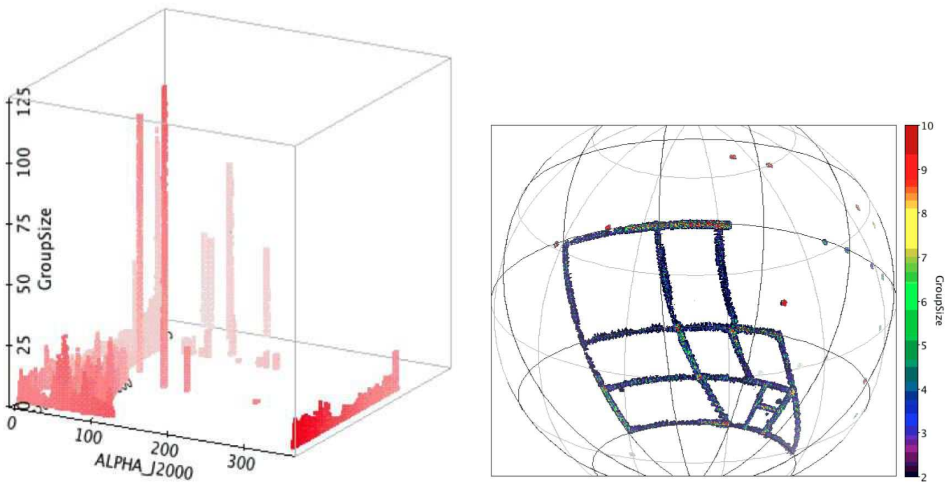

Figure 5. The number of repeat observations for usable PreCam survey and nightly standard star exposures in *i*-band. On the right is a 3D Cartesian plot of "GroupSize" (number of repeat observations) vs. RA, DEC. On the left, this same information is represented as an RA,DEC plot of the star positions, in which the color of each symbol indicates the "GroupSize" (number of repeat observations). In the left plot, we cut off the color bar at 10 repeat observations; stars (mostly in the nightly standard star fields) with more than 10 repeat observations have a dark red color.

7. Summary

We described here a new survey, called the "PreCam Survey," aimed at creating a new network of *grizY* standard stars in the Southern hemisphere in order to support the photometric calibration of the Dark Energy Survey. The PreCam Survey makes use of a new camera, the "PreCam," mounted on the University of Michigan Department of Astronomy's Curtis-Schmidt telescope at Cerro Tololo. The PreCam project used 100 nights of Curtis-Schmidt time between September 2010 and Jan 2011, including time for engineering and commissioning of the PreCam hardware and software, as well as for 51 nights of useful survey data on sky under clear weather conditions. In this paper, we described the PreCam Survey strategy, operations, observations, data reduction, and photometric calibration. Once analysis of the PreCam data is complete, we plan to publish this new catalog of PreCam *ugriz* standard stars in an upcoming paper.

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The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

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